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Request for grant of a patent

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1.	Your reference	MPC/ 9267 GB
2.	Patent application number *(The Patent Office will fill in this part)*	0306798.0 24 MAR 2003
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	The University of Strathclyde McCance Building 16 Richmond Street Glasgow G1 1XQ
	Patents ADP number *(if you know it)*	4081667001
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4.	Title of the invention	Improvements in and relating to vertical-cavity semiconductor optical devices.
5.	Name of your agent *(if you have one)*	Abel & Imray
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	20 Red Lion Street London WC1R 4PQ
	Patents ADP number *(if you know it)*	174001
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country / Priority application number *(if you know it)* / Date of filing *(day/month/year)*
7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application / Date of filing *(day/month/year)*
8.	Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if: a) any applicant named in part 3 is not an inventor, or b) there is an inventor who is not named as an applicant, or c) any named applicant is a corporate body. See note (d))*	Yes

9.	Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same documents.	
	Continuation sheets of this form	
	Description	26
	Claim*(s)*	6
	Abstract	
	Drawing*(s)*	7 + 7 *lle*
10.	If you are also filing any of the following, state how many against each item.	
	Priority documents	
	Translations of priority documents	
	Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
	Request for preliminary examination and search *(Patents Form 9/77)*	1
	Request for substantive examination *(Patents Form 10/77)*	
	Any other documents *(please specify)*	
11.		I/We request the grant of a patent on the basis of this application. Signature: Abel & Imray (signed) — Abel & Imray Date: 24 March 2003
12.	Name and daytime telephone number of person to contact in the United Kingdom	Matthew Critten (01225) 469914

Fig. 1

(Prior art)

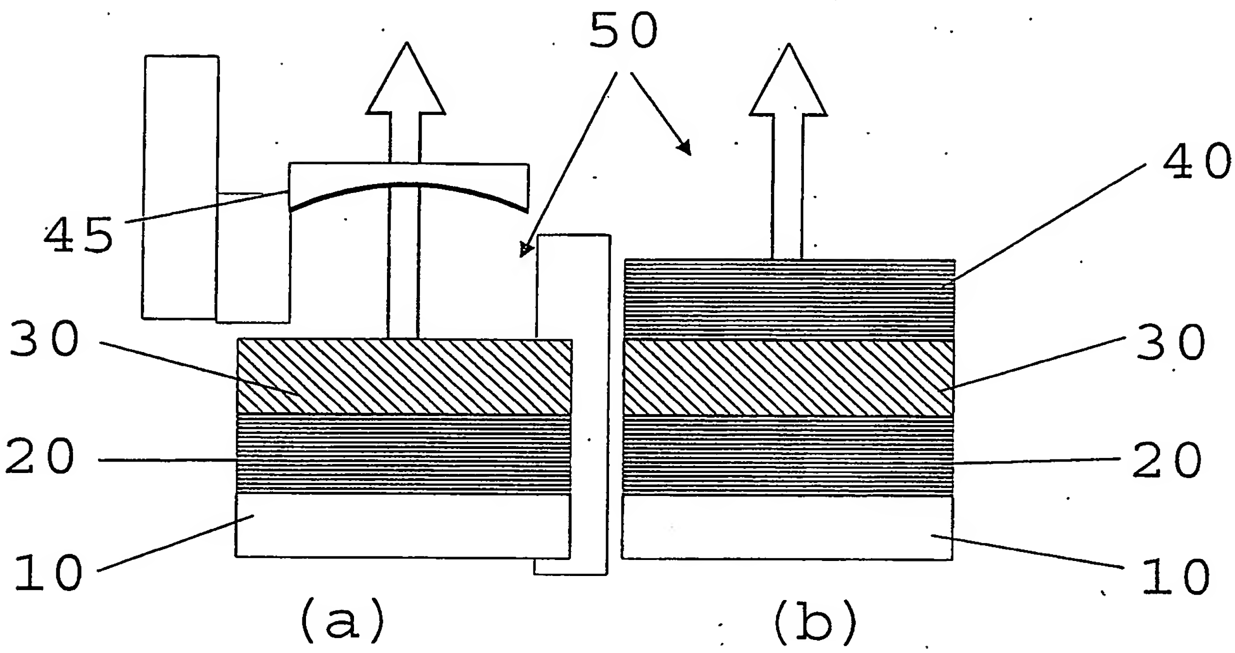

Fig. 2

(Prior art)

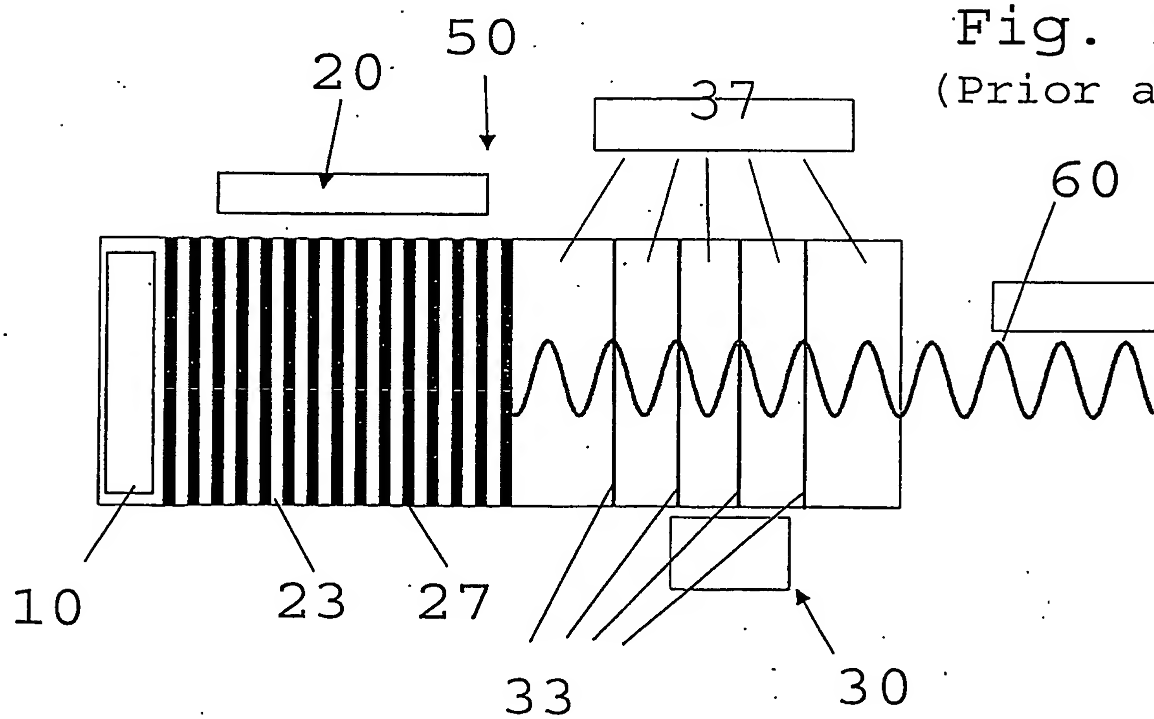

Fig. 3

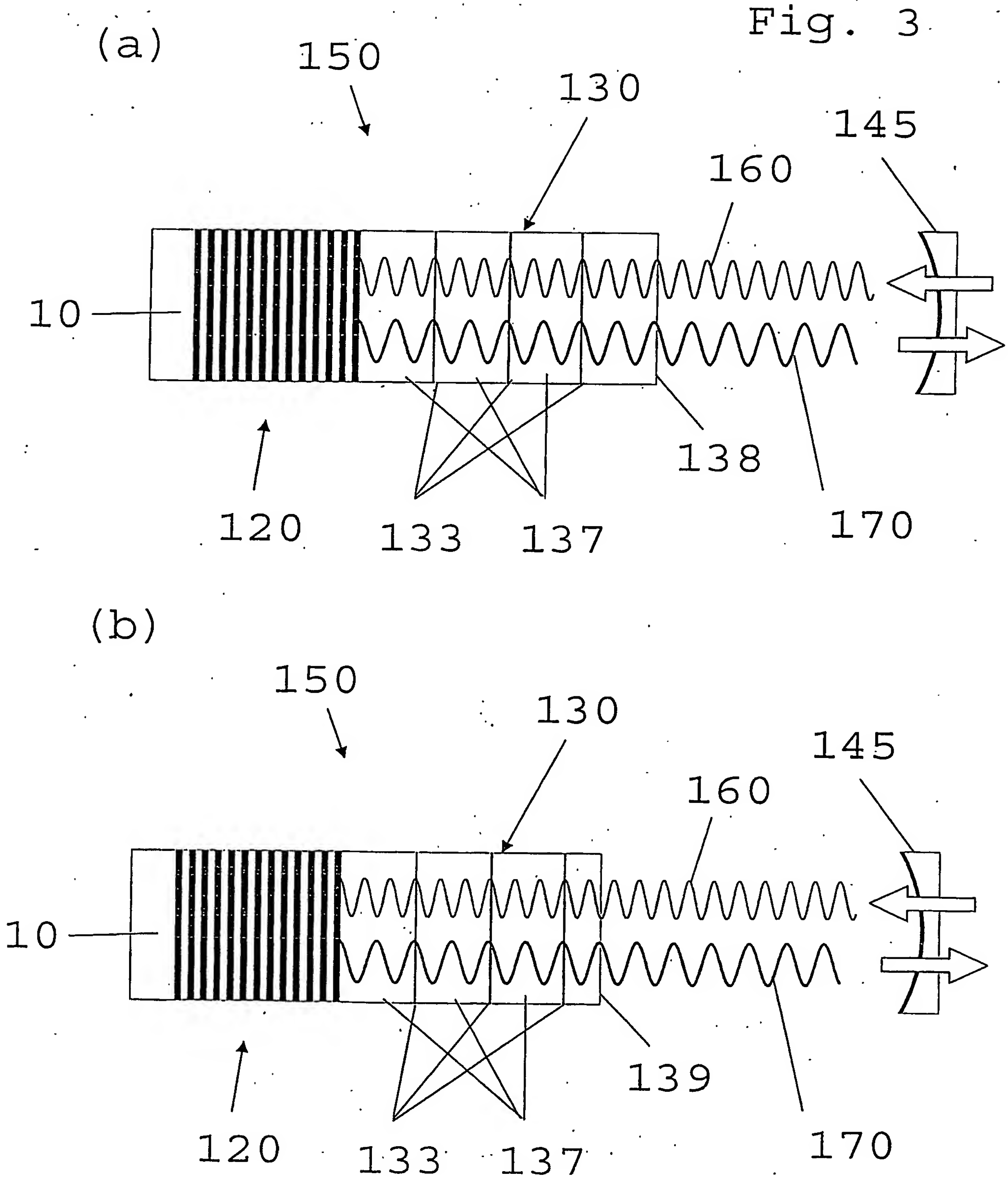
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Fig. 4

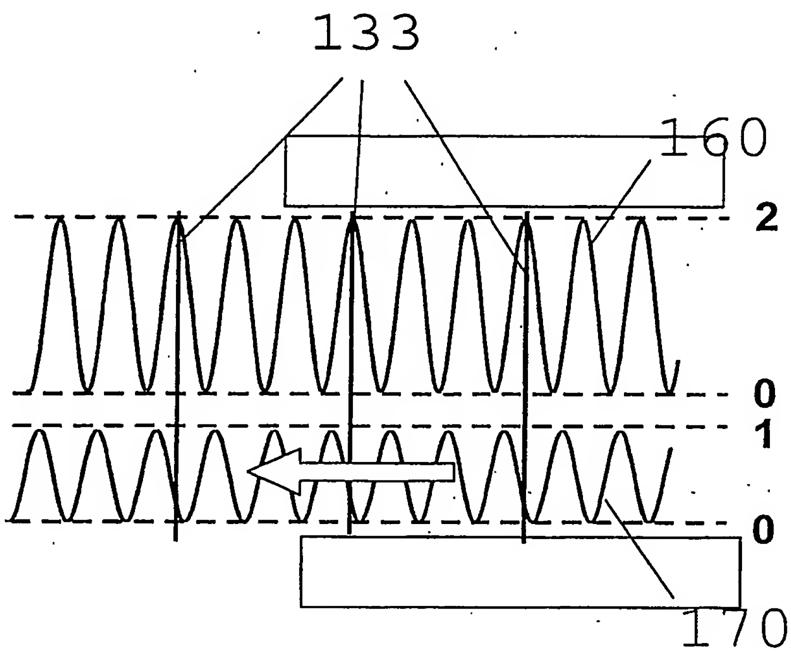


Fig. 5

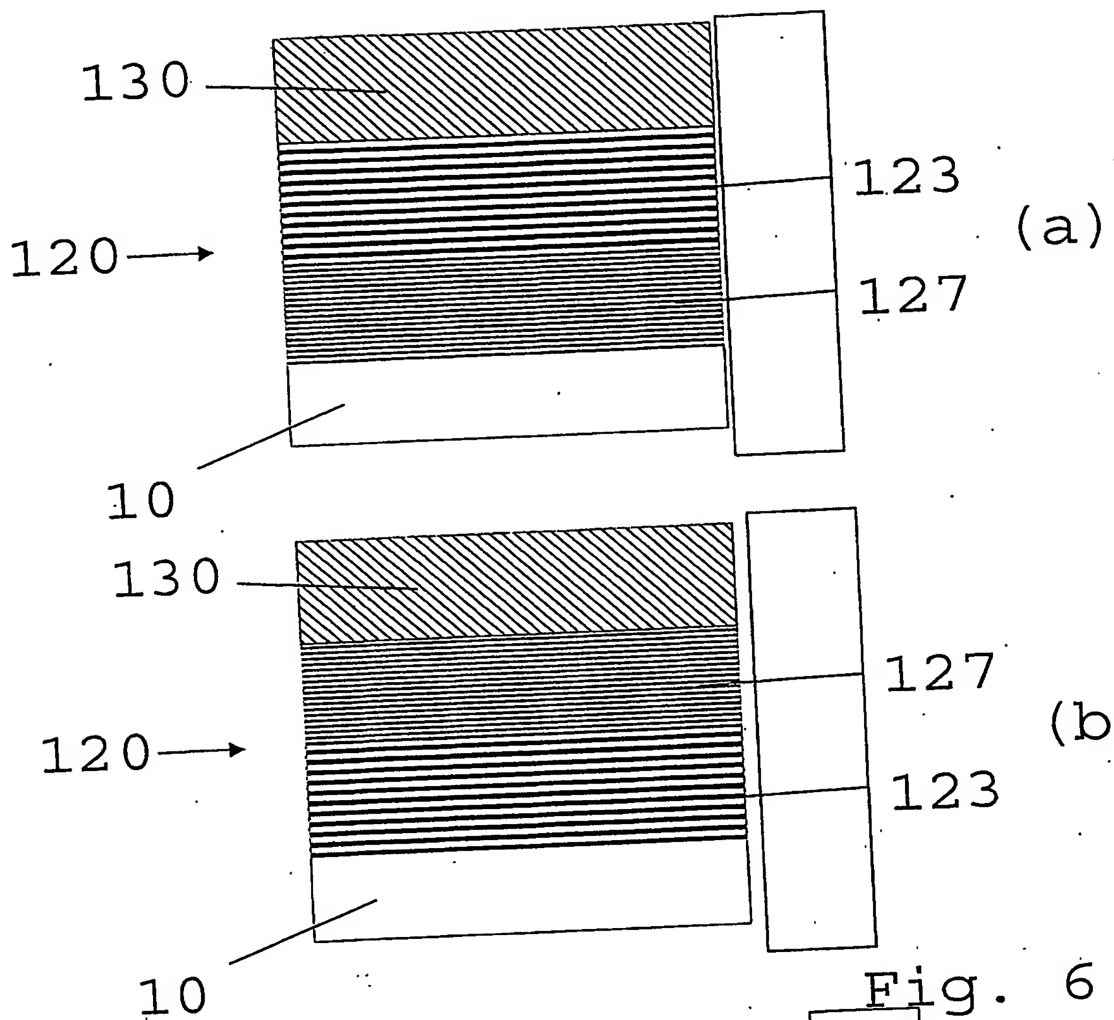


Fig. 6

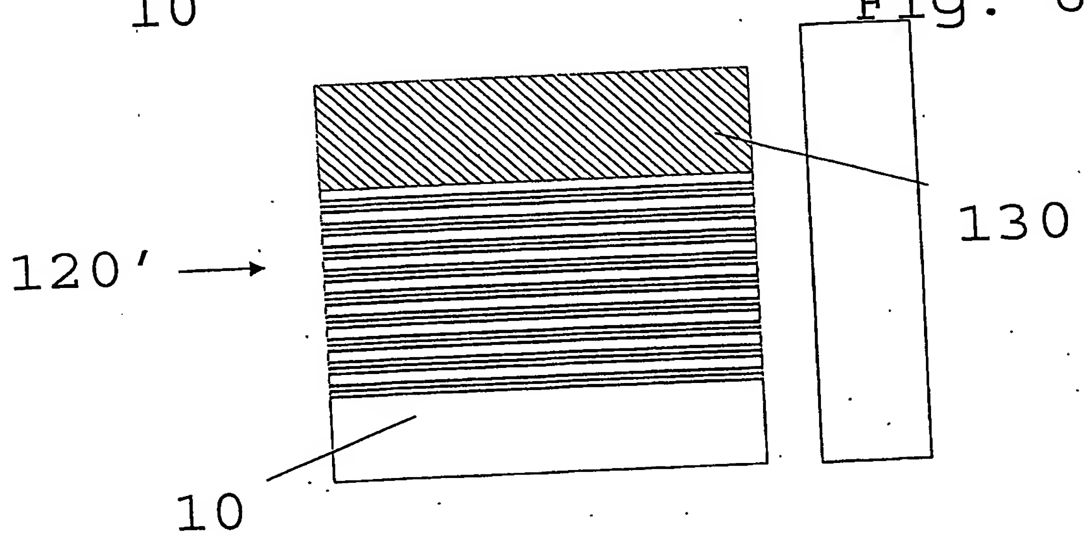
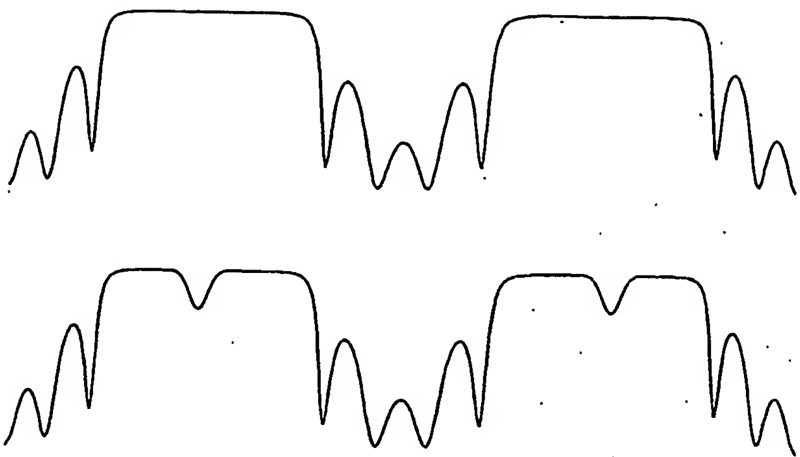


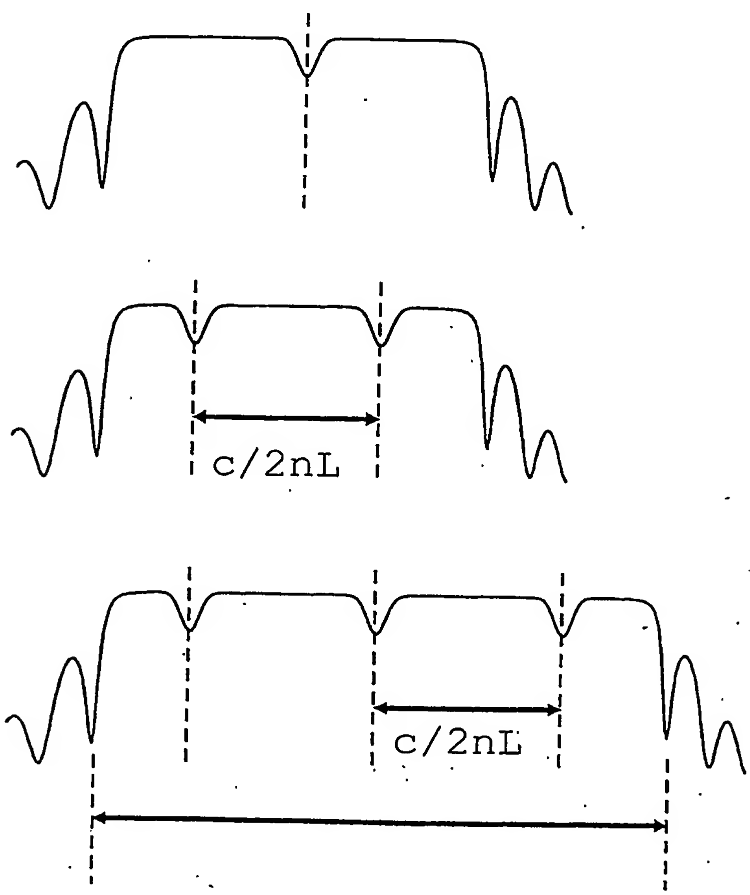
Fig. 7



(a)

(b)

Fig. 8



(a)

(b)

(c)

Fig. 9

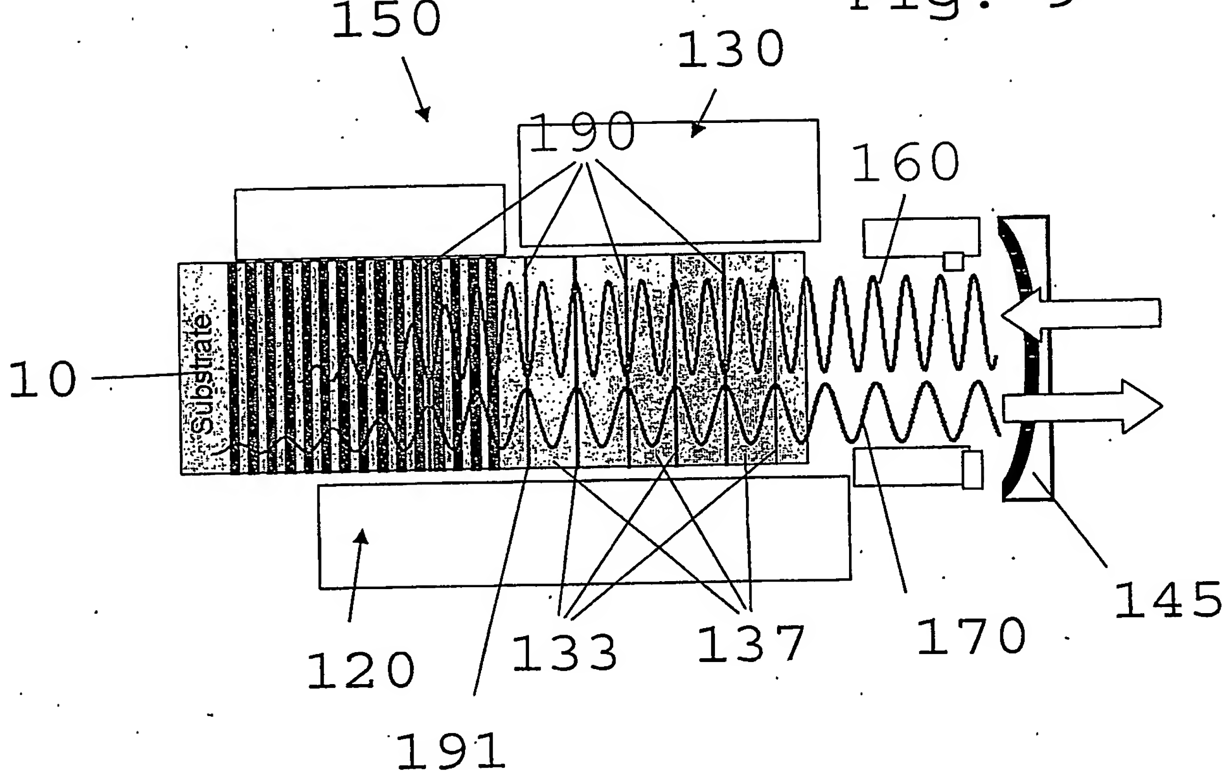

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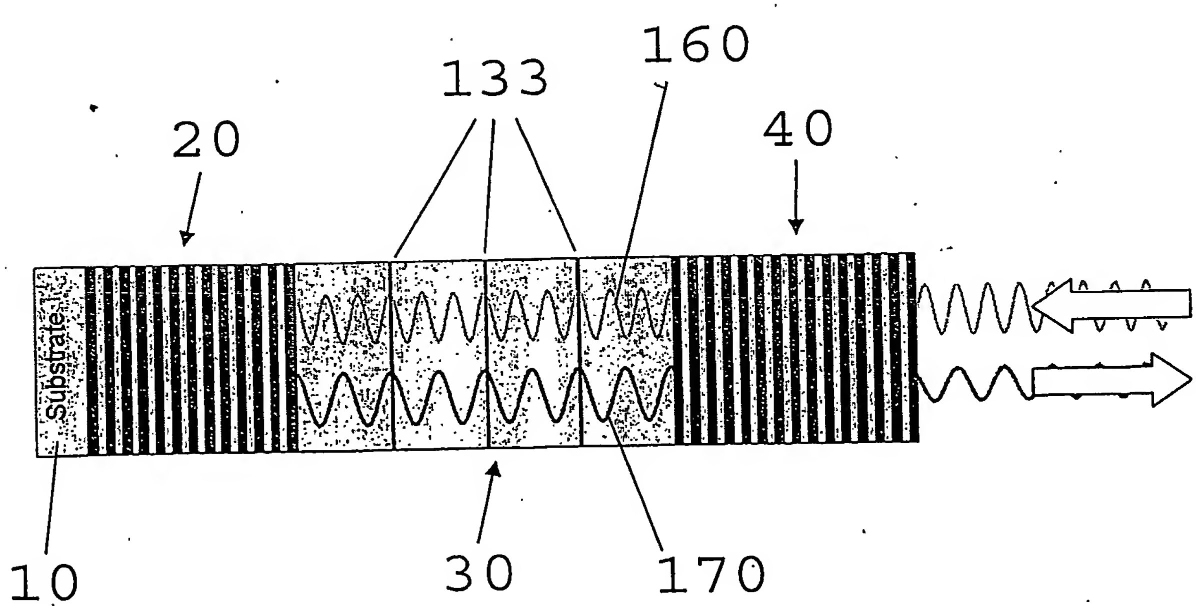
Fig. 10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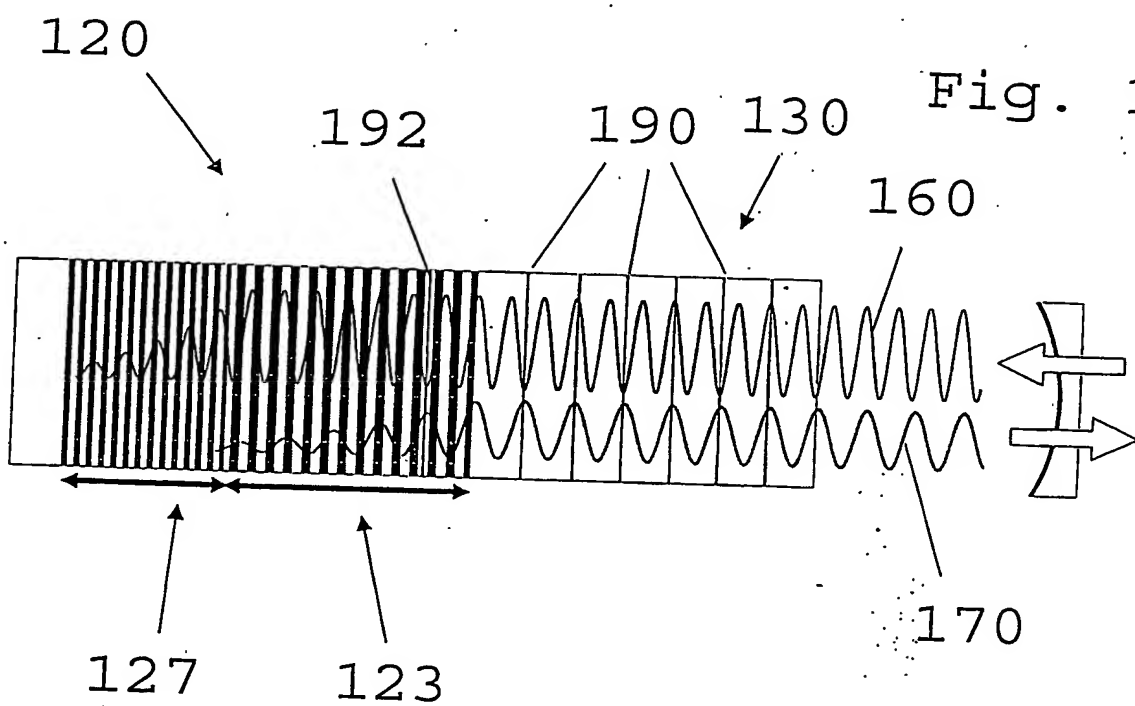

Fig. 11

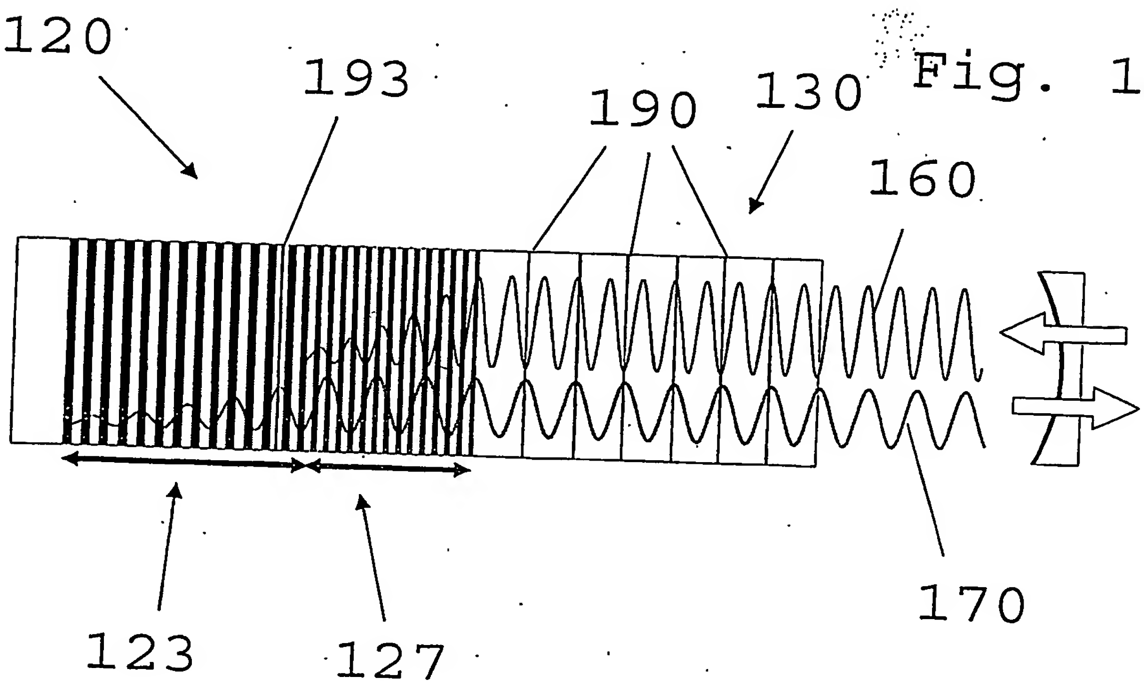

Fig. 12

Improvements in and relating to vertical-cavity semiconductor optical devices

This invention relates to the field of vertical-cavity semiconductor optical devices, in particular to devices such as Vertical-cavity Surface-emitting Lasers (VCSELs), Vertical extended-cavity Surface-emitting Lasers (VECSELs) and Vertical-cavity Semiconductor Optical Amplifiers (VCSOAs).

Semiconductor lasers are by far the most common form of laser available in the world today. They are in general fabricated by depositing layers of semiconductor on a substrate material.

Pump energy may be supplied electrically or optically to a semiconductor laser to achieve a population inversion in the active region of the laser.

Most semiconductor lasers are Edge-emitting Lasers (EELs). In an EEL, an active region is formed by sandwiching a layer of semiconductor material having a lower bandgap energy between two layers of semiconductor materials having higher bandgap energies. The active region usually has a higher refractive index than the adjacent layers and so emitted light is confined by the index steps to the active layer. An EEL thus emits light in a direction in the plane of the active layer. Mirrors providing feedback for lasing action can be provided by various means, including cleaving the end-faces of the semiconductor wafer forming the laser or providing Bragg gratings in the plane of the active layer.

A disadvantage of EELs is that they produce an output beam that is of relatively poor quality in some respects. The active region, viewed from the edge from which light is emitted is typically much wider than it is high. That asymmetry results in an asymmetric output

beam. Although the small height of the active layer usually results in a beam comprising a single transverse mode in the vertical direction, the larger width usually results in many transverse modes in the horizontal direction. This asymmetric, non-diffraction-limited output beam can make it difficult to use the diode output beam in many applications. Various ways of overcoming that problem have been implemented but all involve increased complexity of manufacture.

Vertical-cavity, surface-emitting lasers (VCSELs) are semiconductor lasers that, in contrast to EELs, emit light in a direction perpendicular to the plane of the active layer (Fig. 1 (b)). Feedback is provided by reflectors in the form of distributed Bragg reflectors (DBRs) 20, 40, provided above and below active layer 30, formed from alternating in the deposited structure thin layers of material of different refractive indices. (Devices have also been fabricated having reflectors comprising a metal layer and a small number of dielectric layers, the metal layer providing improved thermal performance.) The active layer 30 usually includes one or more quantum wells that provide gain. As with EELs, the layers 20, 30, 40 are grown on a wafer substrate 10.

The DBRs 20, 40 consist of alternating quarter wavelength (optical thickness) layers of two or more optically transparent materials with a suitable refractive index contrast to provide a high degree of reflection at the signal (operating) wavelength. When grown monolithically DBR 20 is fabricated from semiconductor material layers on a semiconductor substrate with the subsequent half wavelength (or multiple thereof) laser cavity grown on the upper surface of this mirror 20. This cavity may contain either bulk "gain layers" of active semiconductor or single or

multiple thin layers of active semiconductor material (quantum wells) to provide optical absorption at the pump and device gain at the signal wavelength. These layers are surrounded by an appropriate thickness of "barrier" material to provide carrier confinement, additional pump absorption, and for the maximum gain enhancement appropriate spacing for the quantum wells in order to place them in the antinodes of the oscillating field for maximum gain extraction efficiency, a so-called resonant periodic gain (RPG) arrangement. The gain region may be surrounded by a non-absorbing confinement region to isolate carriers from the device surface and the mirror layers. DBR 40 is then fabricated by deposition of further suitable semiconductor material layers.

This semiconductor chip may be mounted on a suitable temperature-controlled heatsink.

VCSELs provide several advantages over EELs. The very short cavity length (which is approximately the height of the active layer, typically ~1 micron) means that a VCSEL operates in a single longitudinal mode, as its mode spacing is greater than the gain bandwidth of the device. Viewed from the direction of emission, the active layer is symmetric, in contrast to an EEL, and so it is much easier to achieve a circular, symmetric output beam. Moreover, use of a short (approximately one-half to fifteen times the wavelength λ of the emitted light) active region permits the symmetric beam to oscillate on a single longitudinal mode. VCSELs typically have low threshold powers for the onset of laser action and they typically have high modulation bandwidths. They are also very stable.

Vertical-cavity devices may be pumped optically or electrically. A disadvantage of electrical pumping is that a relatively complex structure is often necessary in

the semiconductor chip in order to optimise delivery of current to the active region. In contrast, optical pumping may be achieved with a semiconductor chip having a relatively simple structure.

However, the output power available from a VCSEL is rather low, typically of the order of 1 mW. Whilst that is adequate in many applications, many more applications become available for a semiconductor laser emitting higher powers. The power available from an electrically pumped VCSEL is limited by the difficulty of maintaining a uniform current distribution and single-transverse-mode operation for large drive-current apertures.

Vertical Extended Cavity Surface-Emitting Lasers (VECSELs) are a variation of the VCSEL concept that has been recently developed (M.A. Hadley, et al., "High single-transverse-mode output from external-cavity surface-emitting laser diodes," Appl. Phys. Lett. 63, 1607-1609 (1993)). In a VECSEL (Fig. 1(a)), one of the DBRs 40 is omitted from the device and feedback is provided instead by one or more optical substrates coated with highly reflective dielectric coatings at the signal wavelength (external mirror 45 in Fig. 1).

Pumping may be electrical or optical in the form of pump light provided by commercial diode lasers of suitable wavelength coupled to the device with suitable optics to provide a tight to moderate focus at the surface of the VECSEL chip.

With optical pumping, the VECSEL may act as a mode-converter. A pump diode having a relatively poor, multimode beam may be focused to a relatively tight focus in the active region of the chip, where the beam energy is absorbed and re-emitted in the VECSEL output beam, which is typically a high-quality, single-transverse-mode beam. Although the pump beam is not diffraction limited,

and therefore diverges rapidly from a tight focus, the active region of the VECSEL is sufficiently short for that divergence not to be significant within the active region. Thus energy can be efficiently converted from the poor mode of the pump laser to the good mode of the VECSEL.

Use of an external mirror enables production of higher output powers by permitting single mode operation at larger pumping diameters. Continuous wave (CW) powers of over 0.5 W, and pulse peak powers of over 1 W, have been achieved (M. Kuznetsov et al., "High-power (>0.5 W CW) Diode-pumped Vertical-External-Cavity Surface-Emitting Lasers with Circular TEM_{00} Beams," IEEE Photonics Tech. Lett. 9, 1063-1065 (1997); S. Hoogland et al., "Passively mode-locked diode-pumped Surface-emitting semiconductor laser", IEEE Photonics Tech. Lett. 12, 1135-1137 (2000).

Of course, a laser is essentially an optical amplifier that oscillates due to feedback. Power must be supplied to a laser device to create a population inversion, which provides gain. The power for a semiconductor laser is typically supplied optically or electrically. A certain amount of power (the laser threshold power) must be provided for the laser to lase (oscillate) and feedback must be provided. A laser device that does not include feedback (e.g. a VECSEL without a second mirror) or that is not provided with sufficient power for oscillation will act as an amplifier when light of a suitable wavelength is input into the device. Thus a laser device may be operated as a simple or regenerative amplifier, rather than as a laser. A VCSOA is an example of such an amplifier, typically being a VCSEL or VECSEL operated below its lasing threshold. The device of Fig. 1(a) is shown in more detail in Fig. 2

as an illustrative embodiment of the RPG concept. As explained above, the device comprises an external mirror 45 (not shown in Fig. 2) and a chip 50, which includes a substrate 10, a mirror 20 and an active semiconductor layer 30. The mirror 20 is a DBR formed of a plurality of layers 23, 27, with alternate layers 23, 27 being of semiconductor material having a higher and a lower refractive index respectively. Active layer 30 includes four quantum wells 33, which provide optical gain. Quantum wells 33 are separated from each other and from mirror 20 by barrier regions 37.

In operation, signal light 60 is reflected back and forth between mirror 20 and mirror 45 and interference effects between different passes of the reflected light 60 forms a standing wave in the laser cavity. Barrier regions 37 are grown to a thickness selected to position quantum wells 33 at the antinodes of this standing wave of the signal light 60.

Mohammad Yasin A. Raja *et al.* describe in 'Resonant Periodic Gain Surface-emitting Semiconductor Lasers', IEEE J. Quantum Electron. Vol. 25, No. 6 pp 1500-1512 (June 1989) a vertical-cavity semiconductor laser structure comprising an active region comprising 'a series of quantum wells spaced at one half the wavelength of a particular optical transition in the quantum wells'. They go on to state that '[That] spatial periodicity allows the antinodes of the standing wave optical field to coincide with the gain elements, enhancing the frequency selectivity, increasing the gain in the vertical direction by a factor of two compared to a uniform medium or a nonresonant multiple quantum well and substantially reducing amplified spontaneous emission'. They note that 'Various other optoelectronic devices which depend on the interaction between an

electromagnetic standing wave and a carrier population distribution can also benefit from this concept'. Examples of such devices given include 'amplifiers, modulators, wavelength- and phase-sensitive photodetectors, bistable etalons for low-threshold optical switching, saturable excitonic absorbers for mode-locking applications, self-electrooptic-effect devices (SEED's) and nonlinear elements for wave mixing and phase conjugation'.

In modern modelocked solid-state lasers, asemiconductor device which has generated much interest is the semiconductor saturable absorber mirror (SESAM) or saturable Bragg reflector (SBR) (see, for example, U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au. , IEEE J of Sel Topics Quant Electron, 2, 3, 1996, p435). These devices incorporate a high-quality Bragg reflecting mirror structure in which has been grown an absorber region that absorbs at the wavelength of the mirror structure. A low intensity signal incident on the mirror experiences this absorption, so the reflection of the mirror is compromised to some degree. A high-intensity signal will quickly saturate the single absorber allowing the majority of the signal to experience the full reflectivity of the mirror structure. Such a device, placed in a laser cavity, provides a mechanism for differentiating and selecting between continuous-wave (cw) and modelocked or pulsed operation by providing a preferential gain window for a high intensity intra-cavity pulse. It also promotes self-starting modelocked operation. The pulse is allowed to build from any spontaneous emission and atmospheric noise within the

cavity. There are many forms of such a device, all building on this basic principle.

An object of the invention is to provide an improved vertical-cavity device and a method of fabricating such an improved device.

As just discussed, Mohammad Yasin A. Raja *et al.* teach a vertical-cavity device having resonant periodic gain. They also teach that devices that are not vertical-cavity devices can benefit from the concept of resonant enhancement of an interaction. However, the inventors of the invention described below have invented further applications (other than resonant periodic gain) of the broad concept of resonant enhancement to vertical-cavity devices themselves.

Thus according to a first aspect of the invention there is provided an optical device, comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) a pump-light reflector;

characterised in that the pump-light reflector is arranged to reflect pump light so as to form a standing wave in the device.

The active layer, signal-light reflector and pump-light reflector may be comprised in a monolithic unit, which may be a semiconductor chip. The optical device may be, for example, a VCSEL, a VECSEL or a VCSOA or any other suitable device in which the signal light is reflected through the active layer in a direction not in the plane of the active layer. The signal light

reflector may reflect light in a direction passing substantially perpendicularly through the active layer.

The device may further comprise an element, arranged in the pump standing wave, for interacting with light in the device.

There may be one or more than one of the elements for interacting with light in the device.

The active layer may comprise the element for interacting with light in the device.

The element for interacting with light in the device may interact with the pump light in the pump standing wave. By creating a standing wave in the pump light within the device the efficiency of an interaction with the pump light can be immediately doubled. The element for interacting with light in the device may be a gain element that absorbs the pump light to provide gain to the signal light. For example, the gain element may be a quantum well. The gain element may be in the active semiconductor layer.

The creation of a resonant feature at the pump wavelength in an optically pumped device (which we call resonant periodic absorption - RPA) provides a potential for enhanced pump absorption. Assuming weak absorption, reflection of the pump light by the pump-light reflector immediately improves absorption efficiency. The amount of pump light absorbed is then determined by the position of the absorbing region or individual quantum wells within the resonant standing-wave pump field. The gain element may be arranged at the maximum field position to maximise the gain and therefore provide further pump absorption enhancement. The invention may thus provide more efficient devices due to pump enhancement by placing the active regions at the antinodes of a pump standing wave.

Thus, the gain element may be arranged at or near to an antinode of the pump standing wave. Arranging the gain element at an antinode of the pump standing wave will generally result in twice as much power being absorbed compared with a travelling-wave pumping arrangement. That improvement over the travelling-wave arrangement decreases as the location of the gain element is moved away from the antinode and towards a node of the pump standing wave.

The invention provides a particular advantage when used with "in-well" pumping, where the pump energy is such that it is absorbed only in the quantum wells and therefore overall absorption is relatively low for the device (typically, for example, ~1% for each well). Thus, the gain element may be arranged such that pump light is absorbed in the same region of the active layer as a region from which signal light is emitted. For example, the pump light may be absorbed at a transition within a quantum-well structure. For many devices, formation of a pump standing wave enables use of longer wavelength pump and therefore improved overall laser efficiency due to the lower quantum defect. Potentially the localised carrier concentration associated with 'in-well' pumping could lead to a device with a faster dynamic response time.

Alternatively, the element for interacting with light in the device may be a barrier region adjacent to a quantum well; such an arrangement is known as a 'barrier pumping' scheme.

The element for interacting with light in the device may interact with the signal light. The signal light may form a signal standing-wave by reflection from the signal-light reflector. With careful optimisation of the absorber positions the resonant periodic gain of the

device may also be maintained. The element may be arranged at or near an anti-node in the signal standing-wave. The element may be a gain element that absorbs the pump light to provide gain to the signal light, as described above. Thus, the element may be arranged at or near an anti-node in the signal standing-wave and at or near an anti-node in the pump standing wave. For example, again, the element may be a quantum-well structure, which may be arranged at the anti-nodes of both standing waves and thus may provide both maximum pump-light absorption and maximum gain.

Alternatively, the element may be arranged at or near a node in the pump standing wave. The element may be an absorber. When the pump forms a standing wave, it is possible to place absorber layers within the device at positions of near zero pump field. That allows the layers to absorb the signal and act as a saturable absorber at the laser wavelength as they are not saturated by the pump field, as they are effectively not pumped. The element may then act, for example, as a passive modelocking element or a gain-switching element. Thus, the element may be an absorber at a wavelength of the signal light. The element may be a saturable absorber, which may be a quantum well, which may be used, for example, to modelock the device, to produce a pulsed signal-light output.

The position of the absorber with respect to the signal field may be selected (provided it is still placed at one of the pump field nodes) to specifically tailor the fluence at the absorber and therefore the properties of the device such as the modulation depth; the absorber need not necessarily be at an antinode of the signal light. It would also be possible in a semiconductor system to tailor growth conditions and materials used to

form the absorber, to optimise the performance of the absorber within the device, for example to achieve a faster dynamic response or to change the non-saturable losses.

A second device for interacting with light, comprising a gain element that absorbs the pump light to provide gain to the signal light, may be provided in addition to the signal-light-absorbing element. Thus, a saturable absorbing element may be incorporated into a vertical laser device to encourage or cause pulse production. Integrating the gain and pulse producing elements in a single (monolithic) device may advantageously provide a compact pulsed source, which is simple to align and which has (for example, in the case of a VECSEL-type structure) reduced external cavity complexity and a potentially high repetition rate. This idea builds on the resonant periodic absorption enhancement approach described above in that the pump is reflected in order to produce a pump standing wave. RPA enhancement is desirable but not essential (although care should still be taken to ensure the pump-light absorbers in the gain region do not all lie at nodes of the pump field). Also RPG is also desirable in these devices; thus, the pump-light-absorbing element may be arranged at or near an anti-node in the signal standing wave.

The device may comprise a second pump-light reflector for reflecting the pump light back towards the pump-light reflector. Thus a resonant cavity may be provided for the pump light, providing multiple passes of the element. The second pump-light reflector may provide a deliberately engineered or a latent reflection of the pump beam or may be provided by a device-air interface at a surface of the device. The second pump light reflector may only partially reflect the pump light, in order that

sufficient incoming pump light can pass through it. The second pump light reflector may be positioned such that the pump wavelength matches a longitudinal mode of the cavity formed between the pump light reflector and the second pump light reflector; in that case, pump light may be coupled into the cavity even if the second pump light reflector is highly reflecting at the wavelength of the pump light.

The device may comprise a second signal-light reflector for reflecting the signal light back towards the signal-light reflector. Thus a resonant cavity may be provided for the signal light, providing multiple passes of the element.

The signal-light reflector may comprise a stack comprising a plurality of layers having differing refractive indices, which may be a dielectric stack or a semiconductor stack. The stack may be a DBR.

The second signal-light reflector may be a dielectric stack or a semiconductor stack. The stack may be a DBR (to give a VCSEL-type structure, for example) or it may be a coating on an external mirror (to give a VECSEL-type structure, for example).

The pump-light reflector may comprise a metal mirror or a stack comprising a plurality of layers having differing refractive indices, which may be a dielectric stack or a semiconductor stack. The stack may be a DBR. The pump light reflector may be arranged in line with but further from the active layer than the signal-light reflector. Similarly, the second pump light reflector may be arranged in line with but further from the active layer than the second signal-light reflector.

Alternatively, the pump light reflector may be arranged in line with but closer to the active layer than the signal-light reflector. Similarly, the second pump

light reflector may be arranged in line with but closer to the active layer than the second signal-light reflector.

The second pump-light reflector may comprise a metal mirror or a dielectric stack.

Alternatively the pump-light reflector and the signal-light reflector may be comprised in a single structure. For example, the two reflectors may be formed by a DBR exhibiting two reflection bands. Alternatively, the pump wavelength may be chosen to be sufficiently close to the signal wavelength as to fit within a single reflection band. Thus reflections from at least the signal-light reflector and the second signal-light reflector may result in a cavity or sub-cavity resonance at a signal wavelength at which the active layer provides gain and the device may further comprise a source of pump light at a pump wavelength, with the signal-light reflector also reflecting pump light at the pump wavelength. The inventors refer to this as 'close pumping' and it has the advantage of a low quantum defect and therefore greater efficiency and a potentially faster dynamic response of the device. In order to increase coupling efficiency of the pump (which is a significant consideration when the reflectivity of the top mirror is high at the pump wavelength), it is advantageous to pump at a wavelength corresponding to a Fabry-Perot resonance, 'resonant close pumping'. Thus, it may be that reflections from at least the signal-light reflector and the second signal-light reflector result in a cavity or sub-cavity resonance at the pump wavelength.

Obtaining more than one Fabry-Perot resonance within the reflector's reflection band, can be achieved by increasing the length of the active region (cavity or sub-cavity)or by broadening the reflection band of the

reflector, for example, by oxidation to provide a wide band that spans more than one resonance. Combinations of those alternatives may also be used. The reflection of the pump also removes excess heat from the device due to parasitic pump absorption within the device or at the mirror substrate and substrate/heatsink boundaries.

Thus a monolithic or composite laser structure may be fabricated with a bottom Bragg reflector (which may be distinct or exhibit a double reflectance band) that reflects the pump and signal, such that the pump field is in effect resonant and forms a standing wave.

According to a second aspect of the invention there is provided a method of supplying pump light to an optical device, the device comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction passing out of the plane of the active layer; and

(c) a second signal-light reflector;

characterised in that the method includes the step of supplying pump light to the device at a pump wavelength that is reflected by the signal light reflector.

According to a third aspect of the invention there is provided an optical device comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer;

(c) a second signal-light reflector; and

(d) a pump-light reflector;

characterised in that the signal-light reflector is also the pump-light reflector and the device further comprises a second pump-light reflector, wherein reflections from at least the signal-light reflector and the second pump-light reflector result in a second cavity or sub-cavity resonance at a pump wavelength.

Reflections from at least the signal-light reflector and the second signal-light reflector may result in a cavity or sub-cavity resonance at a signal wavelength at which the active layer provides gain; it may be that the pump wavelength corresponds to a further cavity or sub-cavity resonance resulting from reflections from at least the signal-light reflector and the second signal-light reflector. The inventors have realised that the properties of a vertical-cavity optical device may be engineered by localising absorption and then selecting the position of the localised absorption to control the absorber's interaction with pump light.

Thus, according to a fourth aspect of the invention there is provided an optical device, comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) an absorber;

characterised in that the absorber is arranged in a position in the device that is selected to control absorption of pump light by the absorber.

According to a fifth aspect of the invention, there is provided a method of engineering an optical device, the device comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) an absorber;

characterised in that the method comprises the step of controlling absorption of pump light by the absorber by selecting a position for the absorber in the device.

As discussed above, the position selected may be, for example, at an antinode of a pump standing wave. It may be a position in the device at which pump light is very low, minimal or zero, for example at a node of a pump standing wave or at a position in the device that is not reached by pump light, for example because the pump light is reflected before it reaches that position.

According to a sixth aspect of the invention there is provided an optical device, comprising

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) a pump-light reflector;

characterised in that the pump light reflector is arranged between the signal light reflector and the active layer.

The device may further comprise an element for interacting with signal light in the device, the element being arranged between the pump light reflector and the signal light reflector. The element may be a saturable absorber.

Illustrative embodiments of the invention will now be described in detail by way of example with reference to the accompanying drawings in which:

Fig. 1 is a (a) a prior art VECSEL structure and (b) a prior art VCSEL structure;

Fig. 2 is a prior art VECSEL exhibiting resonant periodic gain;

Fig. 3 is a first example of a (a) resonantly pumped and (b) antiresonantly pumped device according to the invention;

Fig. 4 is a schematic showing a standing-wave pump beam and a travelling-wave pump beam;

Fig. 5 is a schematic of two reflectors having two high-reflectance bands used in the device of Fig. 3;

Fig. 6 is another reflector, having two high-reflectance bands, suitable for use in a device according to the invention;

Fig. 7 is reflectivity spectra for (a) a mirror having two reflection bands and (b) a device according to the invention incorporating the mirror.;

Fig. 8 is three reflectivity spectra showing reflectivity spectra of (a) a Fabry-Perot cavity having a discrete reflection band, (b)a Fabry-Perot cavity having a longer cavity than case (a) and (c) a Fabry-Perot cavity having a wider reflection band than in case (a).

Fig. 9 is a second example of a device according to the invention.

Fig. 10 is a third example of a device according to the invention.

Fig. 11 is a fourth example of a device according to another aspect of the invention.

Fig. 12 is a fifth example of a device according to another aspect of the invention.

As discussed above, vertical cavity surface emitting semiconductor lasers and their derivatives are generally either grown monolithically on a substrate or formed through various processing steps (such as bonding and etching) and can include dielectric mirror coatings. They generally comprise a Distributed Bragg Reflector (DBR) mirror structure consisting of alternating quarter wavelength (optical thickness) layers of two or more optically transparent materials with a suitable refractive index contrast to provide a high degree of reflection at the signal (operating) wavelength. On top of this mirror, as described above, a semiconductor cavity or sub-cavity containing bulk, quantum well or quantum dot gain providing regions is fabricated. The optical thickness of this gain region is an integer number of quarter wavelengths (sub-cavity) or an integer number of half wavelengths (cavity) at the signal wavelength. For optimum device performance in the case of quantum wells or quantum dot active regions the wells or dot layers are surrounded by an appropriate thickness of "barrier" or spacer material to place them within the cavity at the oscillating laser field antinodes for maximum gain extraction efficiency, so-called resonant periodic gain (RPG). These layers in addition to providing carrier confinement, depending on their composition may also provide additional pump absorption (barrier pumping), as described above. The gain region or sub-cavity may also contain non-absorbing confinement regions at its edges in order to isolate carriers from parasitic recombination effects at the device surface and/or the mirror layers. Finally, in order to form a Fabry-Perot cavity, a top mirror reflection is provided either by a coated or grown DBR mirror or by the latent reflectivity of the air/semiconductor interface. The

latter case (VECSEL) the surface reflection forms a weaker Fabry-Perot sub-cavity and the device requires an external mirror or mirror arrangement to form a laser resonator. A vertical cavity semiconductor optical amplifier (VCSOA) is simply a VCSEL operated in gain but below laser threshold or has laser operation frustrated in some way. Pump light is provided by lasers of suitable wavelength and is coupled to the device with suitable optics to provide a tight to moderate focus (typically 10-100um) at the surface of the VECSEL chip. The VCSEL, VCSOA or VECSEL chip may be mounted on a suitable temperature controlled heatsink.

The prior art structures of Figs. 1 and 2 have been discussed above.

In an example embodiment of the invention (Fig. 3(a)), a VECSEL comprises a chip 150 comprising a bottom reflector 120, which is designed such that it exhibits a high degree of reflectivity at both the pump wavelength and at the signal (laser) wavelength. The VECSEL also comprises external mirror 145, which is highly reflective at the signal wavelength (in an alternative embodiment of the invention, a plurality of mirrors replace mirror 145). Active region 130 comprises absorbing elements in the form of quantum wells 133 separated by barrier regions 137.

In use, pump light makes a first pass through active region 130 and is reflected at reflector 120. The reflected light interferes with the incident light and produces a standing wave 160. In this embodiment, absorption of the pump light is by in-well pumping and so a significant amount of pump light remains after a second pass through the active region 130 (the typical single pass absorption of each quantum well 133 is ~1%). The pump light is then reflected at the air-semiconductor

interface 138 at the top of the device, back towards mirror 120. (The pump beam is sufficiently wide for an overlap between the incident and reflected beam to occur even though the incident beam will usually not be normal to the interface.) A proportion of the pump light thus makes several passes of the active region 130 in forming the resonant standing wave 160.

In addition to the pump resonance, and as in the prior art, a standing wave 170 is also established in the signal beam by reflections from the mirrors 120, 145.

Barrier regions 137 have a thickness carefully selected to position quantum wells 133 at the antinodes of both the pump standing wave 160 and the signal standing wave 170, so as to enhance the absorption performance of the device, while maintaining RPG performance.

In the resonantly pumped VECSEL of Fig. 3(a), the pump wavelength matches a sub-cavity resonance (indicated by the maximum at surface 138 in the schematic pump field 160 of Fig. 3(a)).

In an alternative embodiment (Fig. 3(b)), chip 150 is made to a different length, such that surface 139 is at a different distance (in this example, closer) to mirror 120 than surface 138 was. The VECSEL is in this case anti-resonantly pumped (that is, it is pumped at a wavelength between the resonant wavelengths of the Fabry-Perot cavity formed between mirror 120 and interface 139), indicated by a minimum at surface 139 in the schematic pump field 160 of Fig. 3(b). The signal field 170 is in this example resonant with this subcavity. Even though the pump field 160 is antiresonant with the Fabry-Perot cavity between mirrors 120, 139, pump field 160 nevertheless forms a standing wave in active region 130 due to reflection at mirror 120.

The pump absorption enhancement factor for a standing pump wave over the case of a travelling wave pump 180 (illustrated schematically in Fig. 4) is a product of the reflectivity of the lower mirror 120 (and hence varies from 1 to 2) and the absorption enhancement from the positioning of the wells 133 (which varies from 0 to 2, corresponding to all wells 133 at the nodes of the pump field 160 and all wells 133 at the antinodes respectively).

The reflection of both pump and signal can be achieved by engineering reflector 120 in any suitable way.

In the embodiments of Fig. 3, reflector 120 comprises two reflectors 123, 127 (Fig. 5(a)). One DBR 123 is for reflecting the signal and the second DBR 127 is for reflecting the pump. The pump mirror 127 is arranged at the bottom of the semiconductor stack (i.e. further than the signal mirror 123 from the active region 130).

In an alternative embodiment (Fig. 5(b), the mirrors are arranged the other way around, with the signal mirror 123 is arranged at the bottom of the semiconductor stack (i.e. further than the pump mirror 127 from the active region 130). This arrangement has the advantage that a saturable absorber may be arranged between the signal mirror 123 and the pump mirror 127, where it will not be exposed to pump light but will be able to affect signal light. This arrangement has the further advantage that, as the signal light must pass through the pump mirror 127, pump mirror 127 may be grown to have a selected effect on the signal light, for example the pump mirror may tailor the signal in some way, for example by affecting its spectrum.

In another alternative embodiment (Fig. 6), reflector 120′ comprises a double band DBR stack comprising alternating refractive index layers arranged in a pattern contains a simplified sub-structure which exhibits two reflection bands, one at the pump and one at the signal wavelength.

In an alternative embodiment, computer optimisation of the individual layer thickness is carried out to provide the desired reflectivity profile.

Example structures for mirror 120′ are shown in Figs. 5 and 6; however, similar structures could also or alternatively be used for external mirror 145 in a VECSEL or top mirror 40 of a VCSEL.

Fig. 7(a) shows the reflectivity spectrum of mirror 120. Two flat high-reflection bands are visible, with the pump wavelength falling within the shorter-wavelength band and the signal wavelength falling within the longer-wavelength band.

Fig. 7(b) shows the reflectivity spectrum and hence the Fabry-Perot resonances or modes of a pair of mirrors having reflectivity profiles as shown in Fig. 7(a). As is well known, a pair of partially reflecting surfaces separated by physical distance L exhibit transmissivity peaks having a separation in frequency of c/2nL, where c is the speed of light and n is the refractive index of the material between the surfaces (2nL is thus the round-trip optical path length between the surfaces).

The reflectivity profile of Fig. 7(b) shows a deep trough near the middle of each of the broad band of frequencies at which the cavity is otherwise relatively highly reflecting.

As with the sub-cavity resonances at the signal wavelength in a VECSEL device, resonances at the pump for any optically pumped vertical emitter can be

enhanced/removed or manipulated by careful design of the structure or by provision of suitable coatings on the structure.

Fig. 8(a) shows the reflectivity spectrum of a device having a pair of mirrors each having a single high-reflectance band. A resonance, due to reflection between the mirrors, appears within the band. In a further alternative embodiment of the invention, the laser cavity or subcavity is grown to be sufficiently long that more than one of the Fabry-Perot resonances lie within the reflection band of the device (pumping at one of the lower of the resonances within a single mirror band is dubbed resonant 'close' pumping). The modes of this reflector, which are of course separated in frequency by c/2nL (with L in this case being longer than in the case of Fig. 8(a)), are shown in Fig. 8(b).

In a further alternative embodiment, a similar close-pumping effect is achieved by creating a suitably wide reflectivity band, for example by an oxidation process. The modes of this reflector are shown in Figure 8(c). Again, the modes are separated in frequency by c/2nL; the increased width of the reflectivity band means that a shorter cavity length may be used than in the case of Fig. 8(b).

Combinations of these various forms of reflectors are also possible.

In another embodiment of the invention (Fig. 9), in addition to gain quantum wells 123 arranged at the antinodes of a pump standing wave 160 and a signal standing wave 170, a saturable absorbers quantum well 191is arranged at a nodes of the pump standing wave 160. (Nodes 190 of the pump standing wave are nodes which coincide with antinodes of the signal standing wave. However, in alternative embodiments of the invention, the

absorber 191 may be arranged at a position, which is preferably at or near a node of the pump light, that does not coincide with an antinode of the signal standing wave.) The incorporation of a saturable absorber 191 at an optimised position within the laser structure enables pulsed operation by passive modelocking or gain switching element. Positioning the saturable absorber 191 at a node of the pump field 160 avoids pump saturation of the absorber 191. The absorber 191 is carefully arranged in the structure (by careful control of the thickness of barrier region 137 during growth of the structure) to allow maximum saturation by the signal 170 and minimal/zero exposure to the pump light 160. The absorber 191 must saturate before the gain provided by wells 123 saturates, in order to provide a preferential gain window for pulse production. In the prior art, a preferential gain window is usually achieved in, a device comprising a SESAM or SBR, by placing the quantum well at or near the surface of the SESAM or SBR and tightly focusing the signal field at the absorber. In an integrated device embodying the invention, there is more scope for positioning the absorber within the cavity or structure; however, to ensure maximum and rapid absorption, the RPG performance (i.e. the position of the gain wells) of the device may have to be compromised. Such an arrangement may provide, for example, gain switching in a VCSEL and modelocking in a VECSEL.

The invention is also applicable to other vertical-cavity devices.

Fig. 10 shows a VCSEL device of a form similar to that of Fig. 1(b). Pump and signal fields 160, 170 each form a standing wave between mirrors 20, 40. Quantum wells 133 provide gain in the device and are arranged at antinodes of both the pump field 160 and the signal field

170, thus providing resonant enhancement of both pump-light absorption and signal-light gain.

Fig. 11 shows a way in which the mirror of Fig. 5 (a) may be incorporated in a VECSEL. Pump mirror 127 is arranged behind signal mirror 123, that is, further from active region 130. Pump standing wave 160 therefore extends through signal mirror 123. Saturable absorber 192 is positioned at a pump node (and a signal antinode) within signal mirror 123.

Fig. 12 shows an alternative arrangement, incorporating the mirror of Fig. 5(b). In this case, the pump light 160 is reflected by mirror 127 in front of mirror 123, whereas signal light 170 passes through mirror 127 to mirror 123, which is further from active region 130 than mirror 127. In this case, saturable absorber 193 is arranged outside the pump standing wave 160, in mirror 123. (As far as saturable absorber 193 is concerned, there is of course no need for the pump light 160 to form a standing wave).

In some examples of embodiments of the invention, the front surface of chip 50 (i.e., the surface furthest from substrate 10 and mirror 120) is uncoated, coated with a custom mirror coating or antireflection coated.

Claims

1. An optical device, comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) a pump-light reflector;

characterised in that the pump-light reflector is arranged to reflect pump light so as to form a standing wave in the device.

2. An optical device as claimed in claim 1, in which the active layer, signal-light reflector and pump-light reflector are comprised in a monolithic unit.

3. An optical device as claimed in claim 1 or claim 2, in which the device further comprises an element, arranged in the pump standing wave, for interacting with light in the device.

4. An optical device as claimed in claim 3, in which the active layer comprises the element for interacting with light in the device.

5. An optical device as claimed in claim 3 or claim 4, in which the element for interacting with light in the device interacts with the pump light in the pump standing wave.

6. An optical device as claimed in claim 5, in which the element for interacting with light in the device is a gain element that absorbs the pump light to provide gain to the signal light.

7. An optical device as claimed in claim 6, in which

the gain element is arranged at or near to an antinode of the pump standing wave.

8. An optical device as claimed in any of claims 3 to 7, in which the gain element is arranged such that pump light is absorbed in the same region of the active layer as a region from which signal light is emitted.

9. An optical device as claimed in any of claims 3 to 6, in which the element for interacting with light is a barrier region adjacent to a quantum well.

10. An optical device as claimed in any of claims 3 to 9, in which the element for interacting with light in the device interacts with the signal light.

11. An optical device as claimed in claim 10, in which the signal light forms a signal standing-wave by reflection from the signal-light reflector.

12. An optical device as claimed in claim 11, in which the element is arranged at or near an anti-node in the signal standing-wave.

13. An optical device as claimed in any of claims 10 to 12 when not dependent on claim 6, in which the element is arranged at or near a node in the pump standing wave.

14. An optical device as claimed in claim 13, in which the element is an absorber.

15. An optical device as claimed in claim 14, in which the element is an absorber at a wavelength of the signal light.

16. An optical device as claimed in any of claims 10 to 15, comprising a second device for interacting with light, comprising a gain element that absorbs the pump light to provide gain to the signal light.

17. An optical device as claimed in claim 16, in which the pump-light-absorbing element is arranged at or near an anti-node in the signal standing wave.

18. An optical device as claimed in any preceding claim, in which the signal-light reflector comprises a metal mirror or a dielectric stack.

19. An optical device as claimed in any preceding claim, in which the pump-light reflector comprises a metal mirror or a dielectric stack.

20. An optical device as claimed in any preceding claim, comprising a second pump-light reflector for reflecting the pump light back towards the pump-light reflector.

21. An optical device as claimed in claim 20, in which the second pump-light reflector comprises a metal mirror or a dielectric stack.

22. An optical device as claimed in any preceding claim, being a monolithic or composite laser structure fabricated with a bottom Bragg reflector that reflects the pump and signal, such that that the pump field forms a standing wave.

23. An optical device as claimed in any preceding claim, in which the pump-light reflector and the signal-light reflector are comprised in a single reflector.

24. An optical device as claimed in any preceding claim, comprising a second signal-light reflector for reflecting the signal light back towards the signal-light reflector.

25. An optical device as claimed in claim 24, in which the second signal-light reflector comprises a metal mirrora stack.

26. An optical device as claimed in claim 24 or 25, in which reflections from at least the signal-light reflector and the second signal-light reflector result in a cavity or sub-cavity resonance at a signal wavelength at which the active layer provides gain, further comprising a source of pump light at a pump wavelength, wherein the signal-light reflector also reflects pump light at the pump wavelength.

27. An optical device as claimed in claim 26, in which reflections from at least the signal-light reflector and the second signal-light reflector result in a cavity or sub-cavity resonance at the pump wavelength.

28. A method of supplying pump light to an optical device, the device comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction passing out of the plane of the active layer; and

(c) a second signal-light reflector;

characterised in that the method includes the step of supplying pump light to the device at a pump wavelength that is reflected by the signal light reflector.

29. A method as claimed in claim 28, in which the pump wavelength corresponds to a further cavity or sub-cavity resonance resulting from reflections from at least the signal-light reflector and the second signal-light reflector.

30. An optical device, comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) a pump-light reflector;

characterised in that the pump light reflector is arranged between the signal light reflector and the active layer.

31. A device as claimed in claim 30, further comprising an element for interacting with signal light in the

device, the element being arranged between the pump light reflector and the signal light reflector.

32. A device as claimed in claim 31, in which the element is a saturable absorber.

33. An optical device comprising:

(e) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(f) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer;

(g) a second signal-light reflector; and

(h) a pump-light reflector;

characterised in that the signal-light reflector is also the pump-light reflector and the device further comprises a second pump-light reflector, wherein reflections from at least the signal-light reflector and the second pump-light reflector result in a second cavity or sub-cavity resonance at a pump wavelength.

34. An optical device, comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) an absorber;

characterised in that the absorber is arranged in a position in the device that is selected to control absorption of pump light by the absorber.

35. A method of engineering an optical device, the device comprising:

(a) an active semiconductor layer, for providing gain to signal light passing through said active layer;

(b) a signal-light reflector, for reflecting the signal light through the active layer in a direction out of the plane of the active layer; and

(c) an absorber;

characterised in that the method comprises the step of controlling absorption of pump light by the absorber by selecting a position for the absorber in the device.